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NEW RAIN RATE ANALYSES TO ASSESS RAIN ATTENUATION ON SATELLITE EHF COMMUNICATIONS

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SUMMARY

This paper provides estimates of the frequency of occurrence, duration and probability of satellite EHF communication outages due to attenuation by rain. These can be used to determine optimum frequencies, power levels and the need for space diversity of terminals or other alternatives to maintain reliable communications. Ten years of 1 min rain rates at each of 12 U.S. cities were used in conjunction with an attenuation model to quantify communication outages at locations representing a variety of climatic regimes. Analyses of the 1 min rain rates and outage estimates at 10, 30 and 45 GHz for elevation angles of 10°, 30°, 50° and 70° are presented. Keywords: [illegible] Frequency [illegible] Attenuation; Rain. (RR)

KEY WORDS EHF Propagation effects Fading

INTRODUCTION

Attenuation due to rain is the major environmental cause of outages to satellite communication systems employing EHF frequencies. Attenuation models have been developed to calculate the impact of rain on these systems based on rain-rate distributions.[1] One-minute rain rates are recognized as most practical for these path attenuation calculations, but data on 1 min rates are scarce. This has prompted the development of models for estimating 1 min rain-rate distributions.[2, 3]

Attenuation of EHF signals can be significant at relatively low rain rates that occur with varying probabilities just about anywhere in the world. Therefore, more precise rain-rate data are required for locations representing many climatic rainfall regimes. With this in mind, Tattelman and Knight[4] describe a method for extracting and digitizing 1 min rain rates from original analogue rain-gauge recordings. The method employs modern digitizing and filtering techniques to obtain the 1 min data that are ordinarily unreadable. This method was used to extract the rain data used to develop the rain-rate analyses and the outage statistics in this article. These statistics are presented in the form of frequencies of occurrence of outage events, probabilities of outage events, and time durations between outage events.

DATA

Weighing rain-gauge recordings for approximately 300 U.S. weather stations are archived on microfiche at the National Climatic Data Center (NCDC) in Asheville, North Carolina. Ten years of 1 min rain-rate data for 12 locations chosen to represent a variety of climatic rainfall regimes were analysed for this article (rain rates for solid precipitation represent melted values). The locations, the percentage of time it rained at each, and the percentage of the rain data that was missing over the 10 years are provided in Table I.

Missing data represent periods of rain when chart records were unavailable for digitizing. However, hourly totals were available, so it was possible to estimate the percentage of total rain data that was missing at each location. This information was used to adjust the rain-rate analyses by using the following correction factor:

$$\text{Correction factor} = \frac{T_{CH}}{T_{CH} - T_M}$$

where T_{CH} is the total number of clock hours of rain and T_M is the number of clock hours of rain that was missing (i.e. not available for digitization). This correction factor is based on the premise that 1 min rain rates during the missing clock hours are distributed in the same way as the available 1 min data. This is reasonable since missing hours are associated with equipment problems and are not correlated with rain-rate intensity.

The data at all locations except Urbana were obtained from rain-gauge recordings stored at NCDC, and are for the period 1 January 1970 to 31 December 1979. The data for Urbana were obtained from the Illinois State Water Survey, Champaign, Illinois as part of a USAF contract.[5] The Urbana data cover a period of 10·25 years from 1 June 1969 to 31 August 1979. They were obtained using a high-speed weighing rain-gauge recorder described in the reference.

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Table I. Locations for which 10 years of 1 min rain rate data were studied. The percentage of time it rains, and the estimated percentage of the rain data that is missing are provided

Location	Elevation (m)	Percentage of time it rains Jan.	Apr.	Jul.	Oct.	Annual	Estimated percentage of rain data missing
Boston, MA	5	8·7	6·6	3·1	5·4	6·3	2·0
Denver, CO	1610	1·7	4·6	1·9	2·6	2·8	2·7
Grand Junction, CO	1475	2·8	2·1	0·8	2·2	1·8	2·6
Key West, FL	3	1·8	1·0	2·6	2·8	2·3	3·7
New Orleans, LA	1	5·8	3·3	4·5	2·2	4·1	2·2
Omaha, NE	300	2·8	5·4	2·8	4·2	3·7	11·7
Pittsburgh, PA	228	8·6	5·4	3·6	5·5	5·6	7·8
Rapid City, SD	965	2·1	5·8	2·6	2·6	3·0	6·2
San Angelo, TX	580	1·6	1·8	1·6	3·0	1·9	3·2
Santa Maria, CA	72	4·2	1·4	<·1	0·8	1·8	1·2
Seattle, WA	120	14·0	6·5	2·3	7·3	8·1	2·3
Urbana, IL	175	4·7	4·1	2·7	3·6	4·1	1·2*

* This value represents percentage of full operational time

ANALYSES OF ONE-MINUTE RATES

The analyses of 1 min rates presented here are intended primarily to assess the impact of rain on EHF satellite communications. Most previous studies of short-duration rain rates for use in attenuation models provide data in the form of annual rain-rate frequencies of occurrence.[3] However, annual statistics can be very misleading because critical rates are concentrated in only a few months of the year at most locations. A low annual frequency of occurrence of a critical rain rate can be intolerably high in these months. Although annual rain-rate frequencies of occurrence are presented for each location studied, monthly or seasonal rain-rate statistics are preferable for assessing the impact of attenuation caused by rain.

Rain rate duration frequencies of occurrence

The annual average numbers of occurrence of a given rain rate for six duration times are provided for each location in Figure 1. Rain rates are equalled or exceeded during each minute of the specified duration. Actual frequencies of occurrence are plotted for every 0·05 mm/min rate up to 1·00 mm/min, and for every 0·10 mm/min thereafter. Values plotted for a frequency of occurrence of 10^{-1} represent the highest rate that was equalled or exceeded for the specified duration.

Monthly average numbers of occurrences of a given rainrate for six different duration times are provided for the worst (most extreme) month at each location in Figure 2. Values are plotted in the same manner as in Figure 1. The worst month at each location was subjectively chosen from all the monthly plots to 'generally' represent the highest frequencies of occurrence of rain rates for all durations. Frequencies of occurrence for some rates and durations may be higher in other months.

Rain-rate duration probabilities

For many design considerations it is more practical to express the likelihood of events in terms of their probability. The Poisson distribution is an appropriate tool for quantifying random events, such as rainfall occurrences, if the events in any time interval are statistically independent of events in another time interval. In this case, rain events of 5, 10, 15, 20 and 30 min durations have been chosen, and the time interval is a specified month of the year (e.g. July). Since these rain events are independent from year to year, the probability, P, of y rain events in a month can be calculated using the Poisson equation

$$P(y) = \frac{e^{-\lambda}\lambda^{y}}{y!} \qquad (1)$$

where λ is the mean number of events per month. Therefore, the probability of *at least* y occurrences of an event is

$$P(\text{at least } y) = 1 - \sum_{z=0}^{y-1} P(z)$$

One-minute rainfall rates versus duration and the probability of at least one occurrence during the worst month are provided in Table II. Rates corresponding to the probability of at least three occurrences during the worst month are provided in Table III. The worst (most severe) month was subjectively chosen as generally representative of the highest rain rates for each probability and duration. Rain rates for some probabilities and durations may be higher in other months. The 0·1 and 0·9 probabilities in the tables can be used to evaluate the variability of rain rates over the 10 year period.

Table IV presents the longest duration at or above specified threshold rain rates and the month of the year that it occurred. Since these are the most

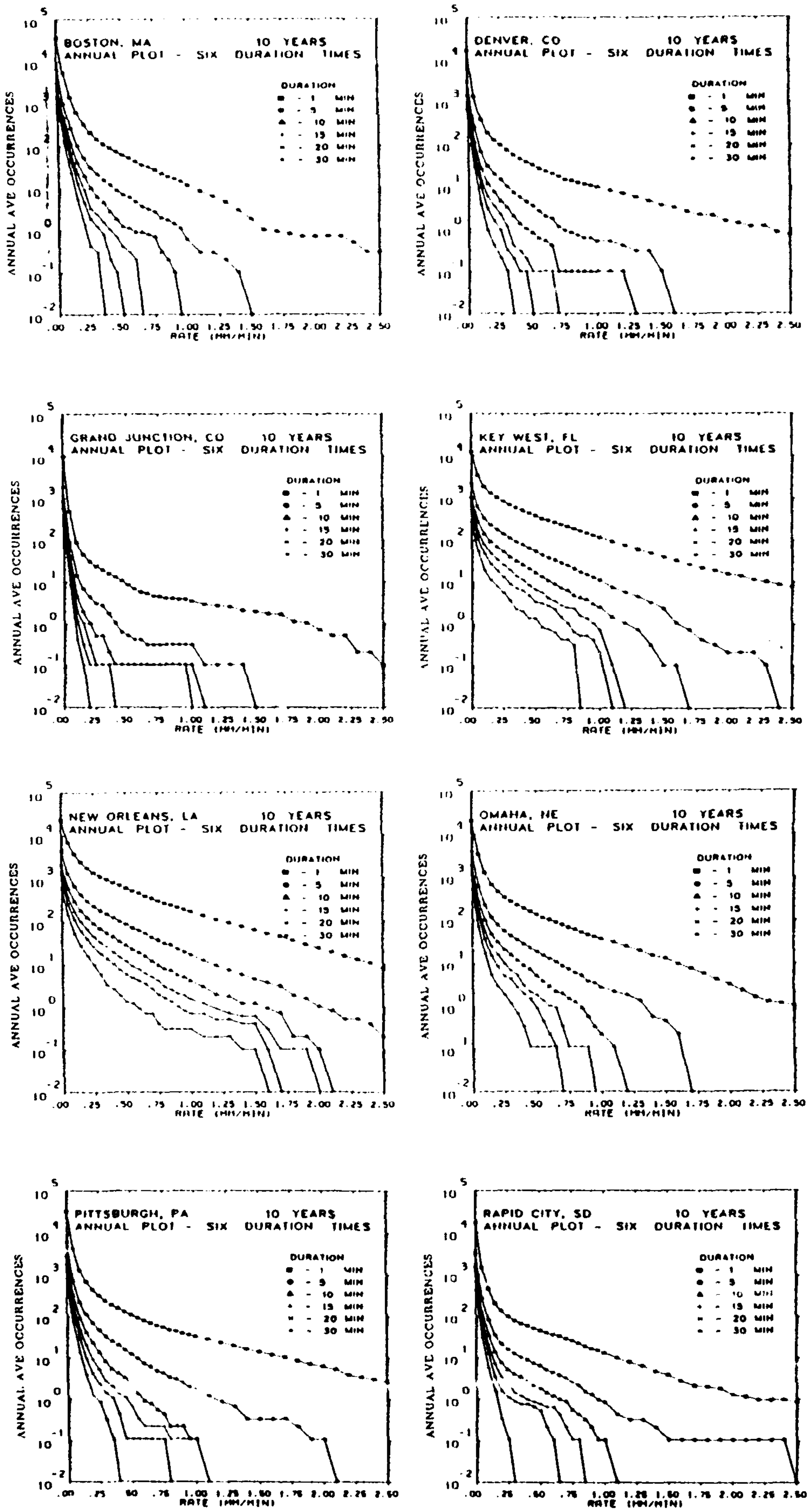


Figure 1. Average annual frequency of occurrence of 1 min rain rates for six duration times

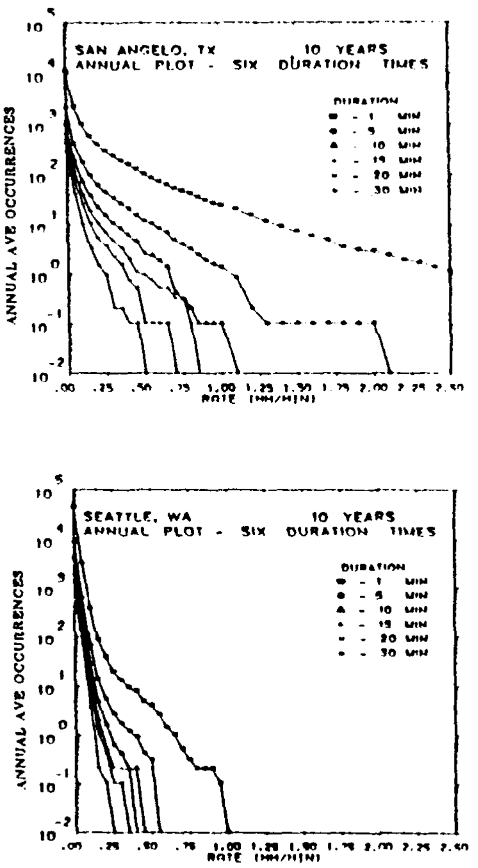


Figure 1 (continued)

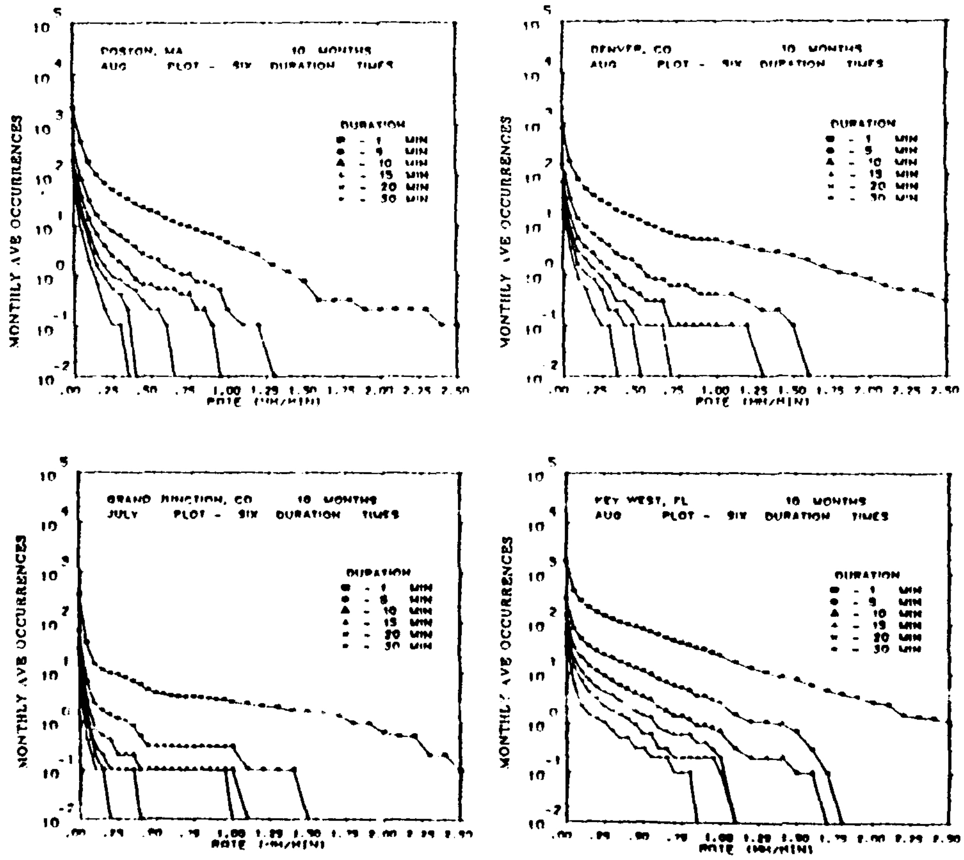


Figure 2. Average worst-month frequency of occurrence of 1 min rain rates for six duration times

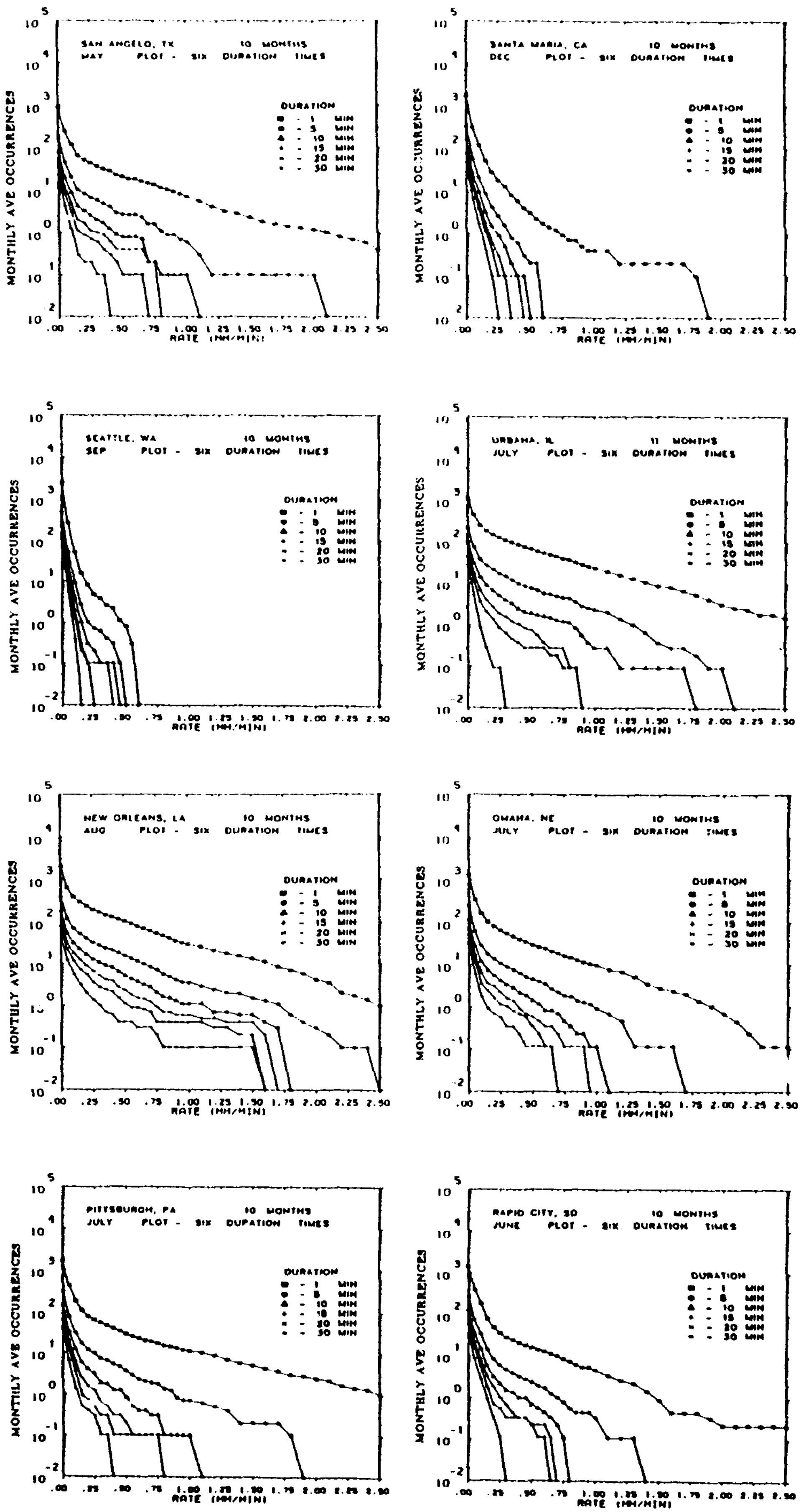


Figure 2 (continued)

Table II. One-minute rainfall rate (mm/min) versus duration and probability of at least one occurrence during the worst month

Location	Worst month	Duration (min) 5 Probability 0·1	0·5	0·9	10 Probability 0·1	0·5	0·9	15 Probability 0·1	0·5	0·9	20 Probability 0·1	0·5	0·9	30 Probability 0·1	0·5	0·9
Boston, MA	Aug.	1·19	0·86	0·48	0·90	0·47	0·26	0·60	0·33	0·16	0·36	0·22	0·13	0·30	0·15	0·09
Denver, CO	Aug.	1·49	0·73	0·38	1·18	0·38	0·22	0·64	0·28	0·13	0·44	0·22	0·09	0·29	0·12	0·07
Grand Junction, CO	Jul.	1·39	0·37	0·10	0·97	0·10	0·06	0·92	0·08	0·04	0·34	0·06	0·04	0·15	0·04	0·03
Key West, FL	Aug.	1·70	1·50	1·03	1·59	1·00	0·59	1·01	0·68	0·40	1·00	0·52	0·24	0·79	0·31	0·10
New Orleans, LA	Aug.	2·38	1·78	1·23	1·76	1·32	0·73	1·64	0·87	0·50	1·54	0·71	0·37	1·45	0·36	0·19
Omaha, NE	Jul.	1·60	1·09	0·68	1·00	0·69	0·39	0·90	0·45	0·24	0·65	0·39	0·15	0·65	0·20	0·09
Pittsburgh, PA	Jul.	1·80	1·02	0·59	0·99	0·52	0·28	0·98	0·29	0·16	0·74	0·20	0·12	0·35	0·14	0·09
Rapid City, SD	Jun.	1·30	0·77	0·50	0·75	0·49	0·24	0·65	0·29	0·18	0·60	0·20	0·14	0·25	0·16	0·11
San Angelo, TX	May	1·97	0·96	0·65	0·99	0·65	0·27	0·77	0·38	0·14	0·64	0·26	0·12	0·34	0·12	0·08
Santa Maria, CA	Dec.	0·57	0·38	0·26	0·44	0·27	0·18	0·39	0·19	0·14	0·30	0·18	0·12	0·20	0·13	0·09
Seattle, WA	Sep.	0·45	0·26	0·16	0·39	0·17	0·12	0·35	0·13	0·10	0·20	0·12	0·09	0·11	0·09	0·07
Urbana, IL	Jul.	1·96	1·38	1·00	1·63	0·57	0·41	0·84	0·51	0·22	0·82	0·28	0·14	0·24	0·11	0·08

Table III. One-minute rainfall rate (mm/min) versus duration and probability of at least three occurrences during the worst month

Location	Worst month	Duration (min) 5 Probability 0·1	0·5	0·9	10 Probability 0·1	0·5	0·9	15 Probability 0·1	0·5	0·9	20 Probability 0·1	0·5	0·9	30 Probability 0·1	0·5	0·9
Boston, MA	Aug.	0·71	0·44	0·33	0·37	0·24	0·17	0·23	0·15	0·12	0·18	0·13	0·09	0·13	0·09	0·06
Denver, CO	Aug.	0·53	0·35	0·23	0·32	0·19	0·10	0·22	0·11	0·07	0·14	0·08	0·05	0·09	0·06	0·04
Grand Junction, CO	Jul.	0·26	0·09	0·06	0·09	0·05	0·03	0·06	0·04	0·03	0·05	0·03	0·02	0·04	0·02	0·01
Key West, FL	Aug.	1·32	1·00	0·75	0·84	0·57	0·37	0·57	0·37	0·19	0·42	0·22	0·13	0·23	0·09	0·06
New Orleans, LA	Aug.	1·70	1·15	0·81	1·10	0·70	0·49	0·72	0·46	0·29	0·50	0·31	0·20	0·29	0·17	0·10
Omaha, NE	Jul.	0·96	0·65	0·44	0·56	0·36	0·20	0·38	0·22	0·11	0·26	0·15	0·08	0·14	0·08	0·05
Pittsburgh, PA	Jul.	0·86	0·56	0·39	0·46	0·27	0·16	0·26	0·15	0·11	0·14	0·11	0·09	0·11	0·08	0·06
Rapid City, SD	Jun.	0·67	0·46	0·27	0·41	0·22	0·16	0·24	0·17	0·13	0·18	0·13	0·10	0·14	0·10	0·07
San Angelo, TX	May	0·81	0·56	0·32	0·42	0·24	0·14	0·26	0·14	0·10	0·15	0·11	0·07	0·10	0·07	0·04
Santa Maria, CA	Dec.	0·33	0·25	0·18	0·23	0·17	0·13	0·17	0·13	0·10	0·15	0·12	0·09	0·12	0·09	0·06
Seattle, WA	Sep.	0·20	0·15	0·12	0·15	0·12	0·09	0·12	0·09	0·08	0·11	0·09	0·07	0·08	0·07	0·05
Urbana, IL	Jul.	1·27	0·91	0·63	0·80	0·38	0·23	0·37	0·20	0·12	0·22	0·13	0·08	0·09	0·07	0·05

extreme occurrences in 10 years (10·25 years at Urbana), the probability that they would occur in that month in any one year is approximately 0·1.

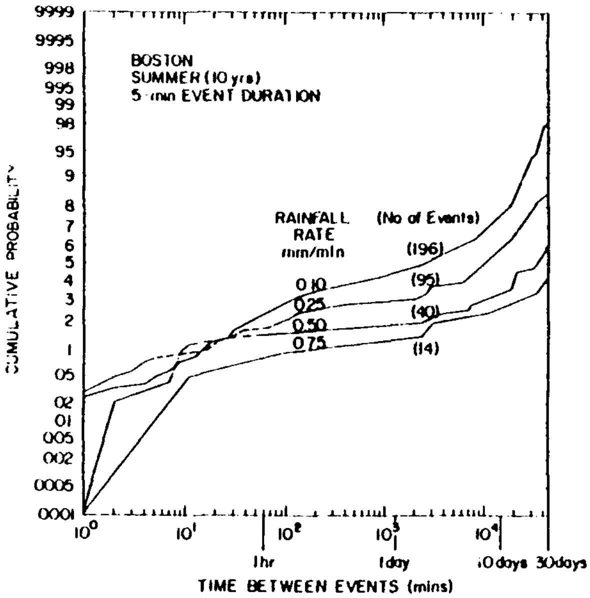
Time between events

To more completely assess the impact of an attenuation outage due to rain, it is also important to know how soon an outage may recur. That is, if it is raining at or above a critical rate and then drops below that rate, what time period would elapse before the critical rain rate was exceeded again? We call the period of time between occurrences of specified rain rates the time between events (TBE). For this study, we considered five threshold rain rates, 0·10, 0·25, 0·50, 0·75 and 1·00 mm/min, which were equalled or exceeded for each of 5 (and 10) consecutive min. An event was considered to occur each time the rain rate exceeded the given threshold for the given duration. When an event occurs (e.g. a rate of at least 0·10 mm/min for five consecutive minutes), what is the TBE until this event recurs?

The TBEs at each location were determined for each meteorological season (e.g. summer is June, July and August). The first and last TBEs for each season were determined by scanning up to 30 days prior to the beginning and after the end of the season. For example, if the first event occurred on 5 June, the first TBE is determined by looking back up to 30 days to the previous event at that threshold rate and duration. If there was no prior event within the 30 day scan, the TBE is considered to be greater than 30 days and is lumped with other TBEs greater than 30 days.

Continuing with this example, if there were no other events for the remainder of the summer season, the scan stops on 31 August and a second TBE greater than 30 days is recorded. If, however, a recurrence happened on 30 August, another TBE greater than 30 days is recorded and the scan continues until the next event, or until 29 September, to determine the last TBE. If there are no more events, there are three TBEs all of which are greater than 30 days. If there are no events during an entire season, a TBE is not tallied. For TBEs up to 30 days, the exact time period is recorded.

The cumulative probability distributions of TBE for Boston, Key West and Urbana during the season with the greatest number of events (summer) are provided in Figures 3, 4 and 5. Data are not provided if a location did not have at least eight occurrences of an event. The numbers of events indicated in the Figures are for 10 summer seasons at Boston and Key West, and 11 summer seasons at Urbana. The probabilities on the ordinate indicate the likelihood of an event recurring within the indicated TBE. For example, in Figure 3(a), the probability of a TBE of one day or less for a 5 min event with a rain rate of 0·10 mm/min is approximately 0·4.



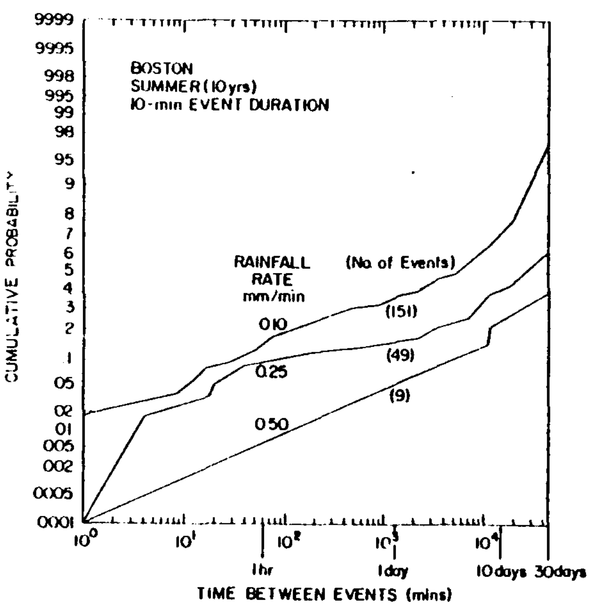


Figure 3. Cumulative probability distribution of time between events categorized by rain intensity at Boston during the summer season for (a) 5 min event duration and (b) 10 min event duration

OUTAGE ESTIMATES

Ordinarily, attenuation models are used to determine path attenuation given the point rain rate. For this exercise, we reversed the order of calculation by determining critical rain-rates that would cause an outage for a specified total path attenuation of 15 dB at 10, 30 and 45 GHz. The USAF Environmental Technical Applications Center (ETAC), Systems Support Section, provided critical rain rates based on the model developed by Crane.[1]

The propagation path length through the rain was determined using mean monthly freezing levels above the ground for the locations and months in Table V. This table specifies the critical rain rates for the indicated path elevation angles at each location.

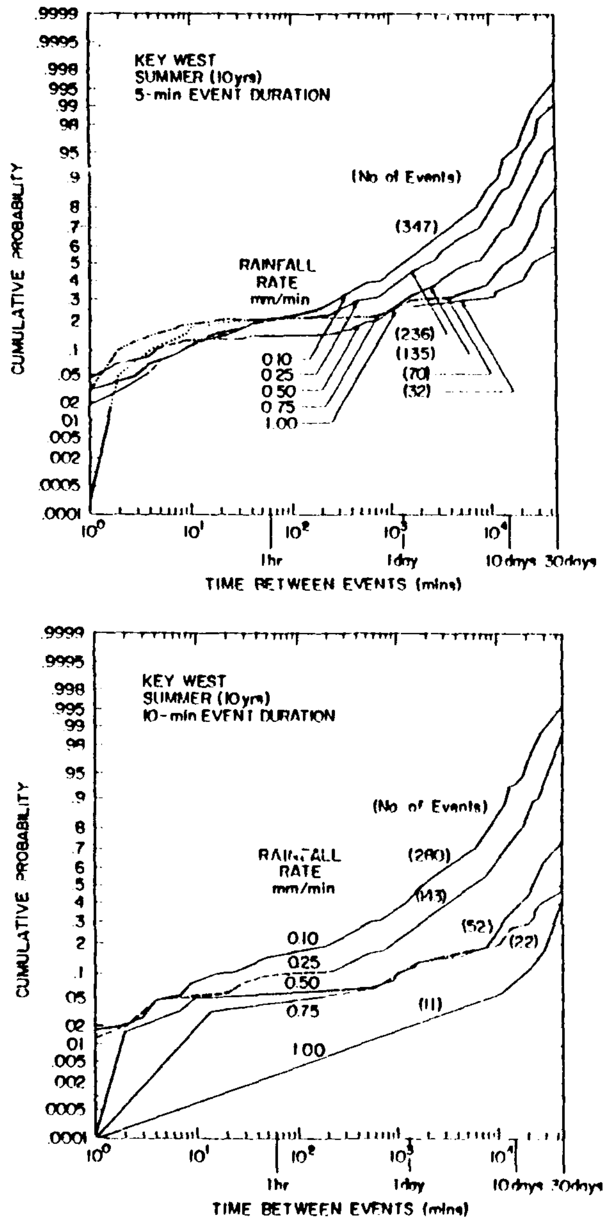


Figure 4. Cumulative probability distribution of time between events categorized by rain intensity at Key West during the summer season for (a) 5 min event duration and (b) 10 min event duration

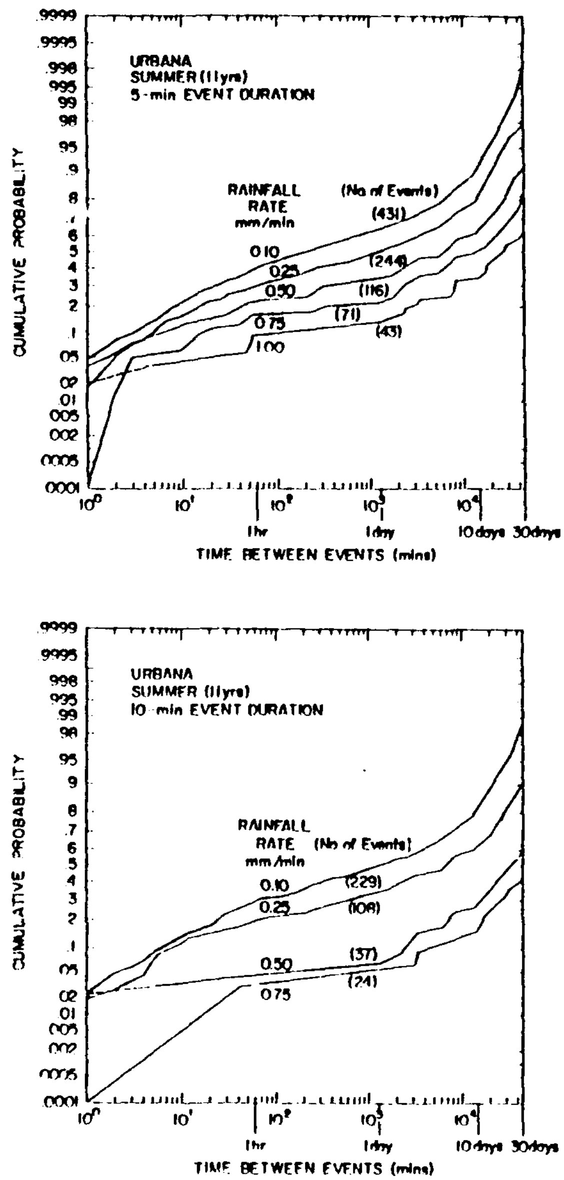


Figure 5. Cumulative probability distribution of time between events categorized by rain intensity at Urbana during the summer season for (a) 5 min event duration and (b) 10 min event duration

Critical rain rates were calculated for the worst month of the year, that is the month that generally had the highest frequency of occurrence of high rain rates during the period studied. Rain intensities are highest during the summer months when freezing levels are also at their highest. Thus the number of outages is greatest during these months. The highest critical rain rates are at locations with the lowest freezing levels above the ground. High elevation locations such as Denver and Grand Junction have relatively low freezing levels above the ground.

Table VI provides the mean percentage of time in the worst month with system outages due to rain. Values were estimated using the rain-rate data for 10 years at each location (11 years at Urbana), and the critical rain rates in Table V. From the table it is apparent that outages due to rain are relatively infrequent. On average, one could expect system availabilities of at least 99·4, 96·1 and 95·3 per cent at 10, 30 and 45 GHz (elevation angle of 10°), respectively. Availabilities increase rapidly with increasing elevation angle.

To put the true impact of rain attenuation into perspective, it should be noted that each minute of rain is not randomly distributed in the month. When it is raining hard enough to cause an outage, it is likely to persist for a period of time. It is the duration of precipitation events causing outages that deserves special attention for EHF satellite communications. Tables VII–IX provide the mean numbers of system outages due to rain with durations of at least 5, 10, 20 and 30 min in the worst month

Table IV. Longest duration (min) of 1 min rates at or above specified threshold rates and the month of occurrence

Location	Threshold rate (mm/min) 0·1	0·2	0·4	0·7	1·0	1·3	1·6	2·0	2·5
Boston, MA	275 Jan.	52 Sep.	23 Sep.	13 Sep.*	7 Jul.†	7 Jul.	3 Oct.	3 Oct.	1 Oct.†
Denver, CO	162 Jun.	47 Aug.	20 Aug.	13 Aug.	12 Aug.	6 Aug.	4 Aug.*	4 Jul.	3 Jul.
Grand Junction, CO	40 Jul.	24 Jul.	19 Jul.	17 Jul.	10 Jul.	8 Jul.	4 Jul.	2 Jul.	1 Jul.
Key West, FL	156 May	74 Aug.	61 Apr.	39 Apr.*	22 Aug.	12 Aug.*	10 Aug.	7 Jul.*	4 Jul.*
New Orleans, LA	205 Feb.	96 May*	86 Aug.	61 Aug.	53 Aug.	44 Aug.	24 Nov.	10 Jul.	6 Apr.
Omaha, NE	142 May	67 Jul.	42 Jul.	18 Jul.	12 Jul.*	9 Jul.	5 Jul.*	3 Jul.‡	3 Aug.*
Pittsburgh, PA	150 May	58 Apr.	27 Jul.	23 Jul.	17 Jul.	7 Jul.*	6 Jul.*	5 Oct.	4 Oct.
Rapid City, SD	149 Jun.	55 Jun.	28 Jul.	16 Jul.	11 Jul.	8 Jul.	8 Jul.	6 Jul.	4 Jul.
San Angelo, TX	161 Apr.	69 Apr.	35 Apr.	19 May	10 May	8 May	7 May	6 May	3 Jun.
Santa Maria, CA	132 Jan.	46 Jan.	19 Sep.	5 Jan.*	3 Jan.	2 Nov.*	2 Nov.*	1 Nov.	0 –
Seattle, WA	82 Feb.	59 Oct.	13 Sep.	2 Aug.*	0 –	0 –	0 –	0 –	0 –
Urbana, IL	91 Oct.	45 May	37 May	25 Jun.	20 Jun.	14 Jun.	10 Jul.*	5 Jul.*	4 May

* Also occurred in one other month
† Also occurred in two other months
‡ Also occurred in three other months

Table V. Critical rainfall rates (mm/min) causing an outage during the worst month for stated frequencies and elevation angles (based on a 15 dB fade margin)

Location	Month	Freezing levels average (km)	10 GHz Elevation angle (in degrees) 10	30	50	70	30 GHz Elevation angle (in degrees) 10	30	50	70	45 GHz Elevation angle (in degrees) 10	30	50	70
Boston, MA	Aug.	4·18	1·07	1·62	2·02	2·18	0·02	0·12	0·20	0·27	0·003	0·050	0·10	0·15
Denver, CO	Aug.	3·13	1·17	1·98	2·56	2·8[illegible]	0·04	0·17	0·27	0·38	0·011	0·076	0·14	0·23
Grand Junction, CO	Jul.	3·45	1·13	1·85	2·36	2·58	0·04	0·15	0·25	0·34	0·008	0·066	0·12	0·20
Key West, FL	Aug.	4·69	1·05	1·50	1·84	1·97	0·02	0·10	0·17	0·24	0·001	0·042	0·08	0·13
New Orleans, LA	Aug.	4·72	1·05	1·50	1·83	1·96	0·02	0·10	0·17	0·24	0·001	0·041	0·08	0·13
Omaha, NE	Jul.	4·31	1·07	1·59	1·97	2·12	0·02	0.12	0·19	0·26	0·003	0·047	0·09	0·15
Pittsburgh, PA	Jul.	3·99	1·09	1·67	2·10	2·27	0·03	0·13	0·21	0·29	0·004	0·053	0·10	0·16
Rapid City, SD	Jun.	2·89	1·21	2·10	2·74	3·01	0·05	0·18	0·30	0·42	0·013	0·085	0·16	0·25
San Angelo, TX	May	3·62	1·12	1·79	2·27	2·47	0·03	0·14	0·23	0·32	0·006	0·061	0·12	0·19
Santa Maria, CA	Dec.	3·29	1·15	1·91	2·46	2·68	0·04	0·16	0·26	0·36	0·009	0·071	0·13	0·21
Seattle, WA	Sep.	3·31	1·15	1·90	2.44	2·67	0·04	0·16	0·26	0·36	0·009	0·070	0·13	0·21
Urbana, IL	Jul.	4·46	1·06	1·55	1·92	2·06	0·02	0·11	0·18	0·25	0·002	0·045	0·09	0·14

Table VI. Estimated mean percentage of the time with system outages due to rain in the worst month for stated elevation angles (based on the frequencies and fade margins listed below)

Location	Month	10 GHz 15 dB Elevation angle (in degrees)				30 GHz 15 dB Elevation angle (in degrees)				45 GHz 15 dB Elevation angle (in degrees)			
		10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	Aug.	0·01	0·00	0·00	0·00	3·30	0·33	0·15	0·10	4·59	1·02	0·40	1·22
Denver CO	Aug.	0·01	0·00	0·00	0·00	0·67	0·10	0·06	0·04	1·50	0·28	0·12	0·07
Grand Junction, CO	Jul.	0·00	0·00	0·00	0·00	0·23	0·02	0·02	0·01	0·68	0·07	0·03	0·02
Key West, FL	Aug.	0·04	0·02	0·01	0·01	2·55	0·61	0·41	0·32	3·56	1·44	0·75	0·51
New Orleans, LA	Aug.	0·06	0·03	0·01	0·01	3·87	0·85	0·60	0·45	4·43	1·95	1·07	0·73
Omaha, NE	Jul.	0·02	0·01	0·00	0·00	2·01	0·30	0·19	0·14	2·78	0·87	0·43	0·22
Pittsburgh, PA	Jul.	0·02	0·01	0·00	0·00	2·02	0·30	0·16	0·12	3·44	0·90	0·40	0·22
Rapid City, SD	Jun.	0·01	0·00	0·00	0·00	0·91	0·14	0·06	0·05	2·64	0·57	0·17	0·08
San Angelo, TX	May	0·01	0·00	0·00	0·00	1·11	0·17	0·10	0·08	1·80	0·48	0·21	0·12
Santa Maria, CA	Dec.	0·00	0·00	0·00	0·00	1·28	0·10	0·04	0·02	3·19	0·49	0·17	0·06
Seattle, WA	Sep.	0·00	0·00	0·00	0·00	1·60	0·03	0·01	0·01	4·71	0·41	0·07	0·02
Urbana IL	Jul.	0·05	0·02	0·01	0·01	1·92	0·52	0·36	0·28	2·48	1·13	0·63	0·43

Table VII. Estimated mean number of system outages due to rain in the worst month for the indicated durations (based on a frequency of 30 GHz and a fade margin of 15 dB)

Location	5 min duration Elevation angle (in degrees)				10 min duration Elevation angle (in degrees)				20 min duration Elevation angle (in degrees)				30 min duration Elevation angle (in degrees)			
	10	30	50	70	10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Denver, CO	0·3	0·0	0·0	0·0	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Grand Junction, CO	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Key West, FL	2·1	0·7	0·0	0·0	0·5	0·1	0·0	0·0	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0
New Orleans, LA	3·2	1·5	0·5	0·3	1·1	0·6	0·0	0·0	0·4	0·2	0·0	0·0	0·1	0·1	0·0	0·0
Omaha, NE	1·7	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Pittsburgh, PA	1·6	0·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Rapid City, SD	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
San Angelo, TX	0·3	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Santa Maria, CA	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Seattle, WA	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Urbana, IL	2·1	0·3	0·1	0·0	0·3	0·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0

Table VIII. Estimated mean number of system outages due to rain in the worst month for indicated durations (based on a frequency of 30 GHz and a fade margin of 15 dB)

Location	5 min duration Elevation angle (in degrees)				10 min duration Elevation angle (in degrees)				20 min duration Elevation angle (in degrees)				30 min duration Elevation angle (in degrees)			
	10	30	50	70	10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	273·7	24·8	10·5	6·9	132·6	10·7	3·8	2·2	60·0	3·3	0·8	0·5	36·0	1·4	0·2	0·1
Denver, CO	55·8	7·7	4·4	2·3	25·9	3·1	1·5	0·7	11·1	0·9	0·4	0·1	06·5	0·4	0·1	0·0
Grand Junction, CO	17·9	1·6	1·1	0·9	8·0	0·5	0·2	0·2	3·2	0·1	0·1	0·1	1·7	0·1	0·0	0·0
Key West, FL	209·8	48·2	31·5	24·0	96·6	20·8	12·5	9·0	41·2	6·9	3·7	2·3	22·9	2·2	1·3	1·1
New Orleans, LA	273·3	69·4	47·4	34·0	128·0	31·2	19·9	13·5	56·5	11·7	6·5	4·0	33·0	5·4	2·7	1·5
Omaha, NE	169·8	23·2	14·0	10·1	79·5	9·7	5·7	3·9	35·0	3·0	1·7	1·1	21·0	1·4	0·7	0·5
Pittsburgh, PA	166·9	22·0	11·3	7·6	77·7	8·4	3·8	2·1	33·2	2·0	0·7	0·3	19·4	0·8	0·4	0·1
Rapid City, SD	74·2	10·5	4·6	3·0	34·7	4·1	1·4	1·0	15·6	1·1	0·3	0·3	8·5	0·5	0·0	0·0
San Angelo, TX	93·1	12·4	7·3	5·4	43·5	5·2	2·9	1·9	19·1	1·5	0·8	0·5	11·3	0·5	0·2	0·1
Santa Maria, CA	109·7	7·6	2·4	0·8	52·4	3·0	0·8	0·2	24·1	1·0	0·1	0·0	14·3	0·3	0·0	0·0
Seattle, WA	132·7	2·3	0·7	0·4	63·2	0·9	0·2	0·1	28·6	0·2	0·0	0·0	17·0	0·0	0·0	0·0
Urbana, IL	159·6	34·5	23·1	16·6	73·1	12·4	7·3	4·9	31·0	3·2	1·6	0·8	17·6	0·7	0·2	0·1

Table IX. Estimated mean number of system outages due to rain in the worst month for the indicated durations (based on a frequency of 45 GHz and a fade margin of 15 dB)

Location	5 min duration Elevation angle (in degrees)				10 min duration Elevation angle (in degrees)				20 min duration Elevation angle (in degrees)				30 min duration Elevation angle (in degrees)			
	10	30	50	70	10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	382·2	82·4	30·9	15·7	186·4	37·7	13·6	6·4	85·3	15·5	4·4	1·6	52·1	7·5	1·9	0·6
Denver, CO	124·8	22·0	9·4	5·4	58·5	9·7	3·8	2·1	26·1	3·7	1·1	0·6	15·6	2·0	0·6	0·1
Grand Junction, CO	55·1	5·0	2·0	1·3	25·1	2·0	0·6	0·4	10·6	0·7	0·2	0·1	5·9	0·3	0·1	0·0
Key West, FL	294·3	112·0	59·5	39·8	136·3	50·6	26·1	16·5	59·0	20·6	9·4	5·2	33·6	10·4	3·7	1·8
New Orleans, LA	373·4	162·7	87·8	58·9	175·5	75·6	40·0	25·5	78·4	32·3	15·8	9·0	46·4	18·3	8·0	4·1
Omaha, NE	231·7	71·6	34·0	17·1	108·8	32·9	14·6	7·1	48·3	13·9	5·0	2·4	29·5	7·4	2·5	0·9
Pittsburgh, PA	287·3	71·7	30·0	15·7	136·3	31·4	12·2	5·4	60·4	11·7	3·7	0·9	36·7	5·8	1·3	0·5
Rapid City, SD	217·1	45·2	12·8	5·8	103·0	20·5	5·2	2·1	46·9	8·6	1·5	0·5	28·2	4·5	0·8	0·1
San Angelo, TX	150·9	39·6	16·6	8·7	71·2	17·8	6·9	3·5	32·1	7·1	2·3	1·0	19·7	3·6	0·9	0·2
Santa Maria, CA	275·7	41·1	13·2	3·9	133·7	19·1	5·7	1·4	62·6	8·3	2·2	0·3	38·4	4·5	0·9	0·1
Seattle, WA	393·5	32·7	5·2	1·0	188·9	15·3	2·3	0·3	86·6	6·4	0·7	0·1	53·3	3·4	0·2	0·0
Urbana, IL	211·0	88·2	44·0	28·3	99·1	37·0	16·6	9·5	43·3	13·9	4·9	2·3	25·1	7·0	1·6	0·4

Table X. Estimated probability of at least three system outages due to rain in the worst month for the indicated durations (based on a frequency of 30 GHz and a fade margin of 15 dB)

Location	Month	10 min duration Elevation angle (in degrees)				20 min duration Elevation angle (in degrees)				30 min duration Elevation angle (in degrees)			
		10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	Aug.	0·99	0·99	0·72	0·36	0·99	0·53	0·05	0·01	0·99	0·13	*	*
Denver, CO	Aug.	0·99	0·59	0·19	0·03	0·97	0·06	*	*	0·84	*	*	*
Grand Junction, CO	Jul.	0·76	0·01	*	*	0·29	*	*	*	0·06	*	*	*
Key West, FL	Aug.	0·99	0·99	0·99	0·99	0·99	0·96	0·70	0·40	0·99	0·38	0·15	0·09
New Orleans, LA	Aug.	0·99	0·99	0·99	0·99	0·99	0·99	0·95	0·75	0·99	0·90	0·50	0·19
Omaha, NE	Jul.	0·99	0·99	0·92	0·74	0·99	0·56	0·25	0·10	0·99	0·15	0·03	0·01
Pittsburgh, PA	Jul.	0·99	0·98	0·73	0·33	0·99	0·24	0·03	*	0·99	0·04	*	*
Rapid City, SD	Jun.	0·99	0·75	0·17	0·07	0·99	0·08	*	*	0·99	0·01	*	*
San Angelo, TX	May	0·99	0·87	0·54	0·29	0·99	0·16	0·04	0·01	0·97	*	*	*
Santa Maria, CA	Dec.	0·99	0·55	0·04	*	0·99	0·06	*	*	0·98	*	*	*
Seattle, WA	Sep.	0·99	0·05	*	*	0·99	*	*	*	0·96	*	*	*
Urbana, IL	Jul.	0·99	0·99	0·97	0·86	0·99	0·60	0·21	0·05	0·99	0·03	*	*

* < 0·01

Table XI. Estimated probability of at least three system outages due to rain in the worst month for the indicated durations (based on a frequency of 45 GHz and a fade margin of 15 dB)

Location	Month	10 min duration Elevation angle (in degrees)				20 min duration Elevation angle (in degrees)				30 min duration Elevation angle (in degrees)			
		10	30	50	70	10	30	50	70	10	30	50	70
Boston, MA	Aug.	0·99	0·99	0·99	0·95	0·99	0·99	0·81	0·21	0·99	0·97	0·29	0·02
Denver, CO	Aug.	0·99	0·90	0·71	0·33	0·99	0·62	0·10	0·02	0·90	0·24	0·01	*
Grand Junction, CO	Jul.	0·99	0·27	0·02	*	0·99	0·02	*	*	0·87	*	*	*
Key West, FL	Aug.	1·00	1·00	0·99	0·99	0·99	0·99	0·99	0·88	0·99	0·96	0·66	0·24
New Orleans, LA	Aug.	0·99	0·99	0·99	0·99	0·99	0·99	0·99	0·99	0·99	0·99	0·98	0·76
Omaha, NE	Jul.	0·99	0·99	0·99	0·97	0·99	0·99	0·83	0·42	0·99	0·94	0·39	0·06
Pittsburgh, PA	Jul.	0·99	0·99	0·99	0·90	0·99	0·99	0·70	0·05	0·99	0·92	0·14	0·01
Rapid City, SD	Jun.	0·99	0·99	0·88	0·34	0·99	0·98	0·18	0·01	0·99	0·76	0·03	*
San Angelo, TX	May	0·99	0·99	0·96	0·68	0·99	0·96	0·36	0·07	0·99	0·65	0·03	*
Santa Maria, CA	Dec.	0·99	0·99	0·89	0·16	0·99	0·98	0·29	*	0·99	0·75	0·04	*
Seattle, WA	Sep.	0·99	0·99	0·30	*	0·99	0·89	0·01	*	0·99	0·42	*	*
Urbana, IL	Jul.	0·99	0·99	0·99	0·99	0·99	0·99	0·82	0·39	0·99	0·91	0·13	*

* < 0·01

for frequencies of 10, 30 and 45 GHz. The number of outages for each duration decreases rapidly with increasing elevation angle.

Tables X and XI provide probabilities of at least three outages due to rain in the worst month for durations of 10, 20 and 30 min at 30 and 45 GHz. Here again, the elevation angle has a profound influence on the likelihood of an outage. At 10 GHz, the only location with a probability greater than 0·01 of three outages is New Orleans, which has a probability of a 10 min outage of 0·10 at 10° and 0·02 at a 30° elevation angle.

Another important consideration is the interval between outages. The information contained in Figures 3–5 can be used to obtain some valuable insight on time between outage events lasting 5 or 10 min. For example, in Figure 3(a) for 5 min rain events in Boston (summer season), cumulative probability of time between events (TBE) is plotted for 0·10 and 0·25 mm/min. These can be used to estimate the TBE for the critical rain rates of 0·12, 0·20 and 0·27 mm/min for elevation angles of 30°, 50° and 70°, respectively from Table V. About 10 per cent of the events during the season will recur within 10 min of another event. Between 20 and 25 per cent of the events recur within an hour of another event.

At Key West (Figure 4(a)), about 20 per cent of the 5 min events at critical rain rates for elevation angles of 30°, 50° and 70° recur within an hour of another event. At Urbana (Figure 5(a)) 30 to 40 per cent of the 5 min events at critical rain rates recur within an hour of another event.

SUMMARY AND CONCLUSIONS

Analyses of 10 years of 1 min rain data are presented for 12 U.S. locations (10-25 years at Urbana). These analyses can be used to determine the frequency of occurrences of outages, their durations, and probabilities based on critical rain rates causing an outage. The critical rain rates can be determined using an attenuation model, such as the one developed by Crane.[1]

Based on the Crane model, critical rain rates were determined for various elevation angles for frequencies of 10, 30 and 45 GHz and a fade margin of 15 dB at the 12 locations studied. Outage statistics were estimated for each location using these and the 1 min rain-rate analyses. The results show the profound influence of the elevation angle of the propagation path on the quantity and duration of outages. Lower elevation angles greatly increase the path length through the rain, with outages resulting at rates as low as 0·001 mm/min (at 45 GHz) at some locations.

Total path attenuation is also greatly influenced by the height of the freezing level, above which the attenuation from ice and snow is negligible. Freezing levels are lowest in the winter so that a much higher rain rate would be required to produce an outage. Of course rain rates are generally much lower during the winter months, further minimizing the likelihood of an outage. Because rain rates and freezing levels are highest during the warmest months, design of satellite EHF communications should be based on conditions during the month of the year when the probability and duration of outages is greatest. Annual statistics that include the very low outage-probability winter months conceal the real impact of rain attenuation on operations.

The new rain-rate data analysed for this article enabled a more detailed assessment to be made of the probabilities and durations of satellite EHF communication outages due to attenuation by rain than has previously been available. Although only 12 locations were studied, they represent a variety of climatic regimes. The results may provide a reasonable indication of rain-event characteristics at other locations with similar climates. We are continuing our research on rain rates by expanding the number of locations studied to about 40, then developing an empirical model to estimate satellite communication outages for any location of concern.

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